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13. ABSTRACT (Maximum 200 words) Ionospheric plasma heating experiments were conducted at Arecibo to investigate generation of ionospheric plasma bubbles, sheet-like ionospheric irregularities, Langmuir waves, upper hybrid waves, and ion Bernstein waves. This research has shed light on physics and effects of HF waves on naturally occurring ionospheric plasma turbulence. Laboratory experiments at MIT's Plasma Science and Fusion Center were carried out, using a student-built large plasma machine, the Versatile Toroidal Facility (VTF) to cross-check the Arecibo results and to simulate ionospheric effect caused by lightning-induced whistler waves. Recent VTF experiments have successfully reproduced the intriguing spectra of HF radio wave-enhanced Langmuir waves observed at Arecibo. Laboratory experiments were also performed to study the combined effect of gravity and magnetic field on the formation of aqueous crystals. This work leads to develop a practical technique for controlled growth of aqueous crystals. A comparison between TOPEX satellite vertical TEC measurements and GPS slant measurements shows that the ionospheric shell model with constant shell height and the assumption of horizontal homogeneity are not accurate for the low-latitude ionosphere.					
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**Radio Wave-induced Ionospheric Plasma Disturbances
and Laboratory Simulation**

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Principal Investigator: Min-Chang Lee, M.I.T.

1. Introduction

Prof. M.C. Lee's Ionospheric Plasma Research Group at MIT's Plasma Science and Fusion Center has been conducting ionospheric plasma heating experiments at Arecibo, using the upgraded HF heater and the 430 MHz incoherent scatter radar, to investigate the generation and evolution of large-scale ionospheric plasma disturbances. These experiments are expected to shed light on physics and effects of high-power radio waves on naturally occurring ionospheric plasma turbulence. The most important discoveries include the generation of "ionospheric plasma bubbles" and "sheet-like ionospheric irregularities" by the vertically injected high-power HF waves. Theoretical research and radar experiments were carried out to study the radar reflectivity of lightning-induced plasma, showing that turbulent scattering of radar waves are determined by the spectral characteristics of plasma density irregularities. In addition, modelling of the ionospheric Total Electron Content (TEC) was made with data recorded with the TOPEX satellite and the GPS satellites.

Laboratory experiments were performed at MIT's Plasma Science and Fusion Center, using a large student-built plasma machine, the Versatile Toroidal Facility (VTF). These experiments are aimed at simulating ionospheric HF heating experiments and lightning-induced ionospheric plasma effects. Recent VTF experiments have successfully reproduced the intriguing spectra of HF wave-enhanced Langmuir waves, including a cascading spectrum and a frequency-upshifted spectrum. Extensive ionospheric plasma effects can be produced by lower hybrid waves excited by the lightning-induced whistler waves. The VTF experiments have shown that lightning-induced whistler waves can be effectively converted into lower hybrid waves and cause plasma effects, such as the spectral broadening of high-frequency plasma waves, and electron/ion energization. Laboratory

experiments were also conducted to demonstrate the important combined effect of gravity and magnetic field on the formation of aqueous crystals. This work can be based on explaining the results of puzzling 1988 Shuttle Discovery experiments, and developing innovative techniques for the industrial growth of aqueous crystals.

Theoretical and numerical analyses of ionospheric radio-frequency (RF) heating have been conducted in collaboration, primarily, with Prof. S.P. Kuo of Polytechnic University. Parametric excitation of ion Bernstein waves by HF wave-enhanced Langmuir waves is studied. This work is aimed at explaining the observed ten-meter scale field-aligned irregularities in a rocket experiment at Arecibo, Puerto Rico. Excitation of the oscillating two stream instability by HF wave-enhanced upper hybrid waves is analyzed to interpret the observed zero off-set frequency component of the radar-detected plasma line spectrum in the Tromso HF heating experiments. The zero set-off frequency Langmuir modes correspond to excited Langmuir waves propagating nearly parallel to the geomagnetic field. A numerical comparison was made to evaluate two schemes generating ELF and VLF waves by modulating the polar electrojet with high power HF waves. This study will be based on to propose future heating experiments in Alaska, using the newly constructed HAARP facility.

2. Summary of Accomplished Research

A. Ionospheric Plasma Bubbles

Ionospheric plasma bubbles were generated by the upgraded Arecibo HF heater in the 1997 heating campaign. These plasma bubbles were observed by radar in the midnight sector with the entire flux tube in darkness. A theoretical model has been proposed to explain the dynamics of density depletions generated during O-mode wave heating of the F layer. We suggest that thermal expansion of plasma away from the heated volume leads to enhanced recombination along the flux tube. In the absence of photoionization sources, density depletions develop along the excited flux tube. The discontinuity of gravity-driven currents at the walls of the depleted region requires development of polarization electric fields. Eastward polarization electric fields of about 2.5 mV/m within the flux tube caused an observed plasma bubble to drift vertically at a speed of 70 m/s [Lee et al., 1998(a)].

B. Sheet-like Ionospheric Irregularities

Larg-scale ionospheric plasma density irregularities, generated by O-mode heater waves at Arecibo, are shown for the first time to have “sheet-like” structures. The irregularities are aligned with the magnetic meridional plane and have scale sizes ranging from a few hundred meters to a few kilometers. This information is deduced from detailed considerations of sequential measurements of radar backscatter power, the controlling magnetic field geometry, and the ionospheric $E \times B$ drifts. The alignment of O-mode-generated irregularities with the magnetic meridional plane, and their disappearance during X-mode heating intervals are consistent with predictions of the thermal filamentation instability model [Kuo and Lee, 1983; Kuo and Schmidt, 1983; Lee and Kuo, 1985]. Reduced radar backscatter power associated with the sheet-like irregularities suggests that plasma hot spots coexist with density reductions during O-mode heating. A digisonde with an antenna pattern overlapping the heated region, located about 100 km to the west of the heater, indicates that the irregularity sheets give rise to the spread F echoes [Lee et al., 1998(b)].

C. Radar Reflectivity of Lightning-induced Plasmas

The scattering of radio waves from lightning-induced plasmas is investigated. The plasmas are modeled as long, perfectly conducting cylinders with surface density irregularities on a scale much smaller than the total channel length. The theoretical wavelength dependence of the radar reflectivity is compared with experimental results obtained with the MIT C-band and S-band radars. It is found that the theory of rough surface scattering predicts two types of inverse power law wavelength dependence for radar reflectivity. They are $1/\lambda$ and $1/\lambda^2$, which correspond to density fluctuations of lightning plasmas with a Gaussian type spectrum and a power-law type spectrum, respectively. By contrast, the theory of long, thin conductors predicts a wavelength dependence of $\lambda^{0.5}$ for radar reflectivity. The experimental observations on common lightning targets free of precipitation masking effects show a mean wavelength dependence of $\lambda^{0.84}$. The observed wavelength dependence lies between the predictions of the two theories. It indicates that the wavelength dependence in these observations is bounded by these two theories. We conclude that the proposed theory for fat overdense plasma channels with

irregular surface and the theory for long, thin overdense channels bracket the observed wavelength dependence [Lee et al., 1998(c)].

D. Ionospheric Modelling

Discrepancies exist between vertically measured ionospheric total electron content (TEC) and slant measurements of TEC that are converted to vertical with the use of a mapping function. Vertical measurements of TEC that are determined by the TOPEX altimeter are compared with equivalent vertical TEC values that are derived from the Global Positioning System (GPS) constellation at latitudes -40° to $+40^\circ$ and longitudes 180° to 360° during periods in 1993, 1994, and 1995. Also, comparisons are made with the AFRL parameterized ionospheric model (PIM) predictions of vertical and equivalent vertical TEC from the same observation points. A trend of disagreement in maximum and minimum TEC values is observed between TOPEX and GPS passes that involve measurements within 20° to the south and to the north of the geomagnetic equator. PIM model predictions, although not exact in value, are consistent in configuration with these observations of overestimation as well as underestimation of TEC. It is shown that the errors are dependent on not only elevation angle, but also azimuth of the line-of-sight direction. The elevation mapping function that relates the line-of-sight TEC to vertical TEC and other assumptions that are made in the application of the ionosphere shell model may be contributing factors to the slant-to-vertical conversion errors [Vladimer et al., 1997].

E. Lab Studies of Lightning-induced Ionospheric Effects

Laboratory experiments have been conducted at MIT, using the student-built Versatile Toroidal Facility (VTF), to investigate some ionospheric plasma effects produced by lightning-induced whistler waves. Lower hybrid waves, generated by the lightning-induced whistler waves, can cause a chain of extensive plasma effects, such as the acceleration of electrons and ions and the spectral broadening of plasma waves. Two mechanisms by which whistler waves generate lower hybrid waves can be important in the ionosphere. One is the simultaneous excitation of lower hybrid waves and low-frequency mode waves by intense whistler waves. The other is the nonlinear mode conversion of

whistler waves into lower hybrid waves in the presence of short-scale field-aligned density striations. The effect of lower hybrid waves on the spectra of Langmuir waves to produce frequency-upshifted and frequency-downshifted Langmuir waves, broadening the spectra of Langmuir waves. The intensity of these beat waves, however, depends upon the angle of wave propagation with respect to the background magnetic field [Lee et al., 1998(d)].

F. Lab Reproduction of Arecibo Results

Laboratory experiments at MIT using the Versatile Toroidal Facility (VTF) have produced “cascading” and “frequency-upshifted” spectra of HF wave-enhanced Langmuir waves resembling the spectra observed in Arecibo experiments. The VTF experiments are well-explained using the source mechanism proposed by Kuo and Lee [1992] to interpret observed Langmuir wave spectra at Arecibo, Puerto Rico. This mechanism is referred to as a nonlinear scattering of parametric decay instability (PDI)-excited Langmuir waves by pre-existing lower hybrid waves to preferentially produce anti-Stokes (i.e., frequency-upshifted) Langmuir waves. Recent radar spectral observations of anti-Stokes Langmuir waves at Arecibo with improved range and time resolution can be reasonably understood in terms of this mechanism [Lee et al., 1997(a)].

G. Controlled Growth of Aqueous Crystals

It has been observed that in the 1988 Shuttle Discovery experiments, crystals grew uniformly throughout the solution and also uniformly on a membrane in the experimental chamber. This was very different from those grown in the laboratories on Earth, where the crystals grew only on the vertical membrane. We propose that the combined effect of gravity and geomagnetic field, in the form of $\mathbf{g} \times \mathbf{B}$ drifts of ions, controls the growth of crystals in aqueous solutions. Based on this theory, the observed distinct difference between space-grown crystals and those grown in laboratories on Earth can be reasonably explained. We have conducted concept-proof experiments on crystal growth under gravity and different magnetic fields in the laboratory. Our experimental results have confirmed the $\mathbf{g} \times \mathbf{B}$ effect, and showed that the uniformity of crystal growth as well as the size and yield of grown crystals can indeed be controlled by the combined effect of gravity and magnetic field. This work is conducive to the understanding of formation of crystals

in nature. Moreover, it may be based on to develop a practical technique for industrial growth of crystals [Lee and Lee, 1997(b)].

H. Theoretical Research on Ionospheric Heating

The HF heater wave-excited Langmuir waves and upper hybrid waves can become pump waves to excite secondary parametric instabilities, which can be responsible for some phenomena observed at Arecibo and Tromsø. We consider the HF wave-excited Langmuir waves propagating along the geomagnetic field as pump waves for the parametric excitation of ion Bernstein waves and daughter Langmuir waves. Analyses of thresholds and growth rates for the conditions of Arecibo's heating experiments show that ten-meter scale ion Bernstein modes can be preferentially excited. This process competes with others that generate "stationary" (i.e., zero-frequency) density striations in the meter scale range. The ten-meter scale ion Bernstein modes are associated with field-aligned density irregularities, which are difficult to be detected by ground-based radars, but they could be detected by rocket-borne probes [Kuo et al., 1998(a)].

It is shown that upper hybrid waves generated by the HF heater wave in the Tromsø's heating experiments can excite oscillating two stream instability near the upper hybrid resonance layer of the heater wave. The sidebands of the investigated parametric instability are obliquely propagating Langmuir waves. These Langmuir waves can be excited in milliseconds and have a broad angular distribution. Thus, those waves propagating obliquely at small angles with respect to the geomagnetic field can contribute to the zero off-set frequency component of the plasma line spectrum detected by a backscattered radar. The analyses also show that the wavelengths of the Langmuir waves have an upper bound and consequently, explain why the zero off-set frequency plasma line has been detected by the EISCAT 933 MHz (UHF) radar, but not by the EISCAT 244 MHz (VHF) radar [Kuo et al., 1997].

Generation of ELF and VLF waves in the HF heater modulated polar electrojet is numerically studied. Illuminated by an amplitude modulated HF heater, the electron temperature of the electrojet is modulated accordingly. Thus, in turn, causes the modulation of the conductivity and thus the current of the electrojet. Emissions are

then produced at the modulation frequency and its harmonics. Two heater modulation schemes are considered. One modulates the heater by a rectangular periodic pulse. The other one uses two overlapping heater waves (beat wave scheme) having a frequency difference equal to the desired modulation frequency. It is essentially equivalent to a sinusoidal amplitude modulation. The nonlinear evolution of the generated ELF and VLF waves are determined numerically, and their spectra are evaluated. The results show that the signal quality of the second (beat wave) scheme is better. The field intensity of the emissions at the fundamental modulation frequency is found to increase with the modulation frequency, consistent with the Tromso observations [Kuo et al., 1998(b)].

3. Students' Dissertations/Theses

One Sc.D. dissertation and one M.S. thesis have been accomplished under the partial support of the AFOSR grant. Daniel T. Moriarty's Sc.D. dissertation reports his research effort using the Versatile Toroidal Facility (VTF) to investigate the current convective instability, which generates low-frequency field-aligned modes. This work is aimed at simulating the naturally occurring ionospheric plasma turbulence at high latitudes. He also investigated the electron beam injection experiments in the VTF and compared the results with those obtained in space experiments. The distinctive differences stem from the following three facts: (1) the background plasma density inhomogeneity is (not) significant in the VTF (space) beam injection experiments, (2) the injected electron beams are (not) energetic enough in space (VTF) experiments to excite high-frequency plasma waves, such as Langmuir waves and upper hybrid waves, and (3) electric currents are present (absent) in the VTF (space) experiments to excite low-frequency plasma density irregularities. The excited whistler waves are found to have a cutoff frequency slightly greater than one half of the electron gyrofrequency [Moriarty, 1996]. Shaun Meredith's M.S. thesis reports the design and construction of a gridded energy analyzer (GEA). The miniature GEA is a non-perturbing probe which is about 3 cm in diameter. Preliminary measurements were made with the GEA, and the deduced ion temperatures were found to be 8 eV. An ion distribution function was determined to be roughly Maxwellian in nature [Meredith, 1998].

4. Patent Application, Publications, and Dissertation/Thesis

(A) Patent

Our discovery of the combined effect of gravity and geomagnetic field on the formation of aqueous crystals can be based on to develop a practical technique for industrial growth of crystals. MIT's Office of Technology Licensing has filed a patent application (United States Patent Application No. 08/808,120).

(B) Publications

1. M.C. Lee, R.J. Riddolls, W.J. Burke, M.P. Sulzer, E.M.C. Klien, M.J. Rowlands, and S.P. Kuo, "Ionospheric plasma bubble generated by Arecibo heater", *Geophysical Research Letters*, 25, 579, 1998(a).

2. M.C. Lee, R.J. Riddolls, W.J. Burke, M.P. Sulzer, S.P. Kuo, and E.M.C. Klien, "Generation of large sheet-like ionospheric plasma irregularities at Arecibo", to be published in *Geophysical Research Letters*, 25, 1998(b).

3. M.C. Lee, Y.R. Dalkir, and E.R. Williams, "Radar reflectivity of lightning-induced plasmas", to appear in July issue of *Journal of Atmospheric and Solar-Terrestrial Physics*, 60, 1998(c).

4. J.A. Vladimer, M.C. Lee, P.H. Doherty, D.T. Decker, and D.N. Anderson, "Comparison of TOPEX and GPS TEC measurements at equatorial anomaly latitudes", *Radio Science*, 32, 2209, 1997.

5. M.C. Lee, R.J. Riddolls, and D.T. Moriarty "Laboratory studies of some ionospheric plasma effects caused by lightning-induced whistler waves", to appear in July issue of *Journal of Atmospheric and Solar-Terrestrial Physics*, 60, 1998(d).

6. M.C. Lee, R.J. Riddolls, K.D. Vilece, N.E. Dalrymple, M.J. Rowlands, D.T. Moriarty, K.M. Groves, M.P. Sulzer, and S.P. Kuo, "Laboratory reproduction of Arecibo

experimental results: HF wave-enhanced Langmuir waves' Geophysical Research Letters, 24, 115, 1997.

7. M.C. Lee and C.H. Lee, "Combined effect of geomagnetic field and gravity on the formation of crystals", Geophysical Research Letters, 24, 607, 1997.

8. S.P. Kuo, J. Huang, and M.C. Lee, "Parametric excitation of ion Bernstein waves by parallel-propagating Langmuir waves in a collisional magnetoplasma", Journal of Atmospheric and Solar-Terrestrial Physics, 60, 121, 1998(a).

9. S.P. Kuo, M.C. Lee, and P.A. Kossey, "Excitation of oscillating two stream instability by upper hybrid pump waves in ionospheric heating experiments at Tromsø", Geophysical Research Letters, 24, 2969, 1997.

10. S.P. Kuo, J. Faith, M.C. Lee, and P.A. Kossey, "Numerical comparison of two schemes for the generation of ELF and VLF waves in the HF heater-modulated polar electrojet", Journal of Geophysical Research, 103, 4063, 1998(b).

(C) Students' Theses/Dissertations

1. D.T. Moriarty, "Laboratory studies of ionospheric plasma processes with the Versatile Toroidal Facility (VTF)", Doctor of Science Dissertation, Department of Nuclear Engineering, M.I.T., 1996.

2. S.L. Meredith, "Construction of a gridded energy analyzer for measurements of ion energy distribution in the Versatile Toroidal Facility, Master of Science, Department of Nuclear Engineering, M.I.T., 1998.